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Conceptual Framework for Lightning Risk Management in Substations Based on Multi-Layered Protection

Krisna Sing
Pembangunan Panca Budi University, Medan, Indonesia

ABSTRACT

Keywords:
lightning risk management; layered protection; surge arrester; isolation coordination; substation.

This article presents a conceptual framework for lightning risk management at substations that emphasizes a defense-in-depth approach as the primary strategy for technical and operational risk reduction. The proposed framework integrates an understanding of lightning hazard (strike density, local climate, topography), asset vulnerability (isolation coordination, clearances, and BIL per equipment), and failure consequences (service reliability, safety, CAPEX/OPEX costs) into a standards-based risk management cycle. The protection layers are conceptualized from external mitigation (shielding/air-termination, down-conductors, and low-impedance grounding systems), internal protection (surge arresters and insulation coordination), to detection and control layers (lightning current monitoring, event recording, condition-based maintenance). The framework also maps the process of establishing target protection levels using the ALARP risk matrix, conceptually determining arrester locations/powers, and the governance of technical inspections and audits throughout the asset lifecycle. Integration of substation digital data (IEC 61850) to improve event observability and maintenance policy feedback is also proposed. While remaining theoretical (without calculations), this framework provides systematic guidance for utilities in developing layered protection policies that are adaptive to tropical climate variability, budget constraints, and reliability demands, while also serving as a basis for further quantitative studies.

Corresponding Author:

Krisna Sing
Pembangunan Panca Budi University, Medan, Indonesia
E-mail : krisna@gmail.com

INTRODUCTION

Substations are critical nodes in power systems because they facilitate voltage transformation, load shedding, and power flow regulation between transmission and distribution levels. In humid tropical climates, the threat of lightning, with its high spatial-temporal variability, is a dominant source of disturbances, triggering protective tripping, insulation degradation, and even service outages. These impacts are not only technical (flashover, overvoltage, dielectric aging), but also operational and economic (reduced reliability, reactive maintenance costs, and safety risks). In practice, partial or single-equipment-oriented protection approaches often fail to capture the interconnectedness between external hazards, internal vulnerabilities, and systemic consequences at the substation level. In principle, lightning risk management requires the integration of three components: hazard characterization (strike intensity, ground conditions, topography, and conductive layout), asset vulnerability assessment (isolation coordination, clearances, Basic Insulation Level (BIL), and grounding quality), and consequence evaluation (reliability implications, personnel safety, and lifecycle costs). Traditional frameworks often stop at meeting minimum standard requirements or focus on the installation of surge arresters without ensuring alignment with grounding systems, return current paths, and condition-based maintenance practices. This gap weakens protection effectiveness because lightning energy paths, traveling wave phenomena, and inductive/capacitive coupling between equipment are not considered holistically.

Technical literature and standards have provided guidelines for external lightning protection, insulation coordination, and arrester placement around transformers and switching equipment. However, there is still a conceptual gap in orchestrating the layers of protection—external, internal, and detection/control layers—into a risk management cycle that adapts to the context of tropical substations, budget constraints, and the demands of digital substation interoperability. In many cases, design and operational decisions have not been explicitly linked to acceptable risk targets (e.g., the ALARP principle) or to feedback mechanisms from event data (event records, lightning counters) for predictive maintenance. This article proposes a defense-in-depth conceptual framework for lightning risk management at substations. The framework integrates: site hazard and exposure mapping; risk target policies and acceptance criteria; the design of external protection layers (air-termination, down-conductors, and low-impedance grounding); internal protection layers (surge arresters and isolation coordination between equipment gateways); and condition-based maintenance detection, monitoring, and governance layers. This integration is complemented by risk-based prioritization principles, so that technical decisions—such as arrester location/power, return path arrangement, and inspection strategies—are tied to policy-measured reliability and safety objectives, although the article remains theoretical without calculations. The main contribution of this paper is to formulate a comprehensive concept map that links lightning hazard, equipment vulnerability, and systemic consequences at the substation level, to develop a layered protection orchestration pattern that aligns with the coordination of isolation and grounding performance, to position digital monitoring (e.g., IEC 61850 integration) as a feedback source for continuous improvement and maintenance, and to offer a decision-making flow based on the ALARP principle to reconcile technical requirements and practical constraints (cost, downtime, and site access). The article is structured as follows. The following sections detail the elements of a layered protection framework and the relationships between them. Next, conceptual guidelines for risk targeting and implementation priorities in substations are discussed. The final section presents operational implications and a research agenda for more detailed quantification, along with practical recommendations for utilities in designing resilient and adaptive lightning protection policies.

METHODS

Design Approach

This research uses a theory-driven conceptual approach to develop a lightning risk management framework based on layered protection for substations. The focus is on synthesizing theory, standards, and practice without numerical calculations, resulting in a work flow, design principles, and operational checklists.

Literature Acquisition & Curation

1. Source mapping with lightning protection standards and insulation coordination, substation guidelines (grounding concepts, arrester placement), power system reliability literature, and substation digital practices.
2. Inclusion criteria with direct relevance to the substation, tropical/humid climate context where available, and utility practice acceptability.
3. Knowledge extraction with core concepts (e.g. lightning current paths, traveling waves, insulation coordination), control/monitoring (event recording, lightning counters), and risk governance (risk matrix, ALARP).

Conceptual Synthesis & Framework Formulation

The framework is structured through three stages: Domain abstraction by mapping three components of hazard risk, vulnerability, consequences, and their interrelationships at the asset, inter-asset, and substation system levels. Layered protection orchestration involves constructing external layers (air-termination, down-conductor, and low-impedance grounding), internal layers (surge arresters and inter-gate isolation coordination), and detection/control layers (monitoring, event logging, and condition-based maintenance policies). Risk governance integration involves linking technical decisions to risk targets through a qualitative risk matrix and the ALARP principle, including prioritization of actions when conflicting constraints (budget, downtime, site access) occur.

Implementation Flow (Conceptual Workflow)

1. Site Hazard Profile i.e. collect hazard indicators (strike density, soil/topography characteristics, structural exposure) and form a substation exposure map.
2. Asset Vulnerability Inventory & Mapping namely identification of critical equipment, inlet/outlet interfaces (line entrance, bus, bay), return flow paths, and insulation coordination gaps and grounding quality.
3. Risk Targeting is defining acceptance criteria (safety, reliability, compliance) and desired level of protection; selecting priorities based on service consequences.
4. Layered Protection Design is the design of a cohesive external–internal–detection/control layer arrangement (not a single device), including conceptual placement of arresters, lightning current path arrangement, and monitoring integration.
5. Implementation & Maintenance Plan, namely developing a phased plan (quick wins → structural improvements) and a condition-based maintenance program with observability indicators (event records, visual inspections, non-intrusive periodic measurements).
6. Continuous Improvement Loop using event data to update risk maps, adjust priorities, and validate the effectiveness of protection layers.

Qualitative Validation

Expert elicitation is a structured workshop with practitioners in protection, substation operations, and occupational safety to assess the completeness of the layers and potential missed failure paths. Scenario walk-throughs are tabletop simulations of typical scenarios (direct strike to inlet, induction to control, ground potential rise) to check cross-layer integration. Checklist compliance is an examination of the framework's compliance with standard requirements and local utility practices. Traceability is a linking of each layer recommendation to a specific hazard/vulnerability/consequence in the conceptual risk register.

RESULTS AND DISCUSSION

Synthesis Results of the Risk Map Framework and Protection Orchestration

The Risk Map constructed from literature and practice shows three dominant clusters:

- The hazards include high lightning strike density in tropical climates, ground potential rise (GPR) in soils with varying resistivity, and induction in control loops.
- Vulnerabilities include insulation coordination gaps at the line–bus–bay interface; connection quality and bonding integrity; and uncontrolled return current paths.
- The consequences are repeated protection trips, transformer insulation degradation, and SCADA/IED system disruption.

Layered Protection Orchestration maps controls to each failure mode. The external layer (air-termination, down-conductor, low-impedance grounding) controls incoming energy and GPR. The internal layer (surge arresters, insulation coordination, shielded wiring) limits overvoltages on equipment. The detection/control layer (event recording, lightning counters, IEC 61850 integration) closes the feedback loop for condition-based maintenance. A key finding is that protection effectiveness improves when arrester placement, return current paths, and grounding design are decided as a whole—rather than as single-equipment decisions.

The conceptual risk register generates ALARP-based action priorities:

- Priority I (fast/big impact) is repairing bonding and connections, adding arresters to unprotected entrance gates, auditing the return current path to the main ground grid.
- Priority II (structural) is re-engineering of the local earthing network (grid densification, equipotentialization), alignment of isolation coordination between gates.
- Priority III (operational) is a structured monitoring program (event log, non-intrusive periodic visual inspection), action threshold for condition-based maintenance.

This approach allows for phased decisions within budget constraints and outage windows, while maintaining consistency with the acceptable risk target (ALARP).

Qualitative Validation: Expert Elicitation and Scenario Walk-Through

Workshops and table-top exercises (conceptual) on three typical scenarios—(S1) direct strike at line entrance, (S2) induction to control circuit, (S3) GPR in a lightning storm demonstrated the completeness of layers with external–internal controls, complementary monitoring and the largest gaps are usually found in connection integrity and return current paths. Decision traceability, i.e. each control can be linked to a specific hazard/vulnerability in the risk register, facilitating technical audits. Implementation readiness: quick wins (tidying up bonding, adding arresters at priority entry points) are considered realistic to be implemented without major changes to the assets. Although non-numerical, qualitative validation is sufficient to initiate the implementation of a layered protection policy in a controlled manner.

Operational & Observability Indicators (Non-Quantitative)

The framework proposes event-based indicators to guide maintenance:
Event indicators: number of lightning-related trips per season, lightning counter count, IED/SCADA reset frequency. Asset health indicators: connection/corrosion visual inspection records, bonding integrity testing, spot-check connection resistance (without publishing figures). Governance indicators: level of compliance with isolation coordination checklists and return path documentation. These indicators facilitate feedback loops without having to disclose calculations; they focus on trends and process compliance. A layered approach mitigates single failures, increases resilience to variations in lightning and ground conditions, and is more adaptable to asset upgrades. A monolithic approach (e.g., simply adding arresters) is prone to blind spots because it doesn't control the GPR, return current path, and coupling to the control. cross-layer orchestration is more robust against environmental uncertainty and substation configuration variations.

Compliance with Digital Substation Standards & Practices

The framework aligns conceptually with digital substation isolation, grounding, and documentation coordination practices. Interoperability: Utilizing IEC 61850 for event record collection accelerates root cause analysis (post-event review). Process compliance: Risk registers and checklists facilitate internal audits and compliance reporting without disclosing calculation figures. Digital data integration enhances observability and strengthens continuous improvement. Results show that a layered protection framework anchored by ALARP and supported by digital observability provides a clear operational foundation for utilities to reduce lightning risk at substations—even without calculations—through action prioritization, maintenance feedback loops, and alignment with modern standard practices.

CONCLUSION

This article formulates a conceptual framework for lightning risk management in substations based on defense-in-depth that integrates hazard characterization, asset vulnerability mapping, and consequence evaluation into a risk governance flow aligned with the ALARP principle. The synthesis shows that protection effectiveness is not determined by a single component (e.g., the addition of surge arresters alone), but rather by a coherent orchestration between the external layer (air-termination, down-conductor, and low-impedance grounding), the internal layer (arresters and insulation coordination), and the detection/control layer (event monitoring and condition-based maintenance).

In practice, this framework prioritizes phased actions, including quick wins in the form of bonding/connection arrangements and closing protection gaps at entry points, structural strengthening of the grounding network and harmonizing isolation coordination between gateways, and activation of feedback loops through event recording and periodic audits. This approach is compatible with limited outage windows and budgets, while enhancing observability and traceability of technical decisions through a conceptual risk register and compliance checklist. The paper's key contributions—the risk concept map, the layered protection blueprint, and the ALARP-based decision flow—provide utilities with an operational foundation for reducing lightning risk without requiring initial numerical calculations. A limitation of the paper lies in its non-quantitative nature; therefore, further research is recommended to conduct numerical and empirical validation (e.g., EMT studies, GPR field measurements, and cost-effectiveness evaluations) across various substation configurations and tropical soil conditions. In short, the implementation of this framework enables utilities to manage risks proactively, measurably, and adaptively, while paving the way for future policy development and more detailed quantitative studies.

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